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Efficacy of Management Practices to Mitigate the Off-Site Movement and Ecological Risk of Pesticides Transported with Runoff from Agricultural and Turf Systems

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1. Introduction

Pest management in both agricultural and non-agricultural settings uses established practices and new technologies to control harmful and nuisance pests. Pesticides are an important tool in integrated pest management. Without pesticides a significant percentage of food and fiber crops would be lost, infectious diseases would increase, and valuable native habitats would be devastated by invasive species. In 2000 and 2001, annual world pesticide usage exceeded 2.3 billion kilograms of active ingredient (Kiely et al., 2004). The application of pesticides to targeted areas inevitably results in the transport of a portion of these chemicals and their degradation products to surrounding non-target areas. Pesticides are biologically active compounds designed to interfere with metabolic processes (Matsumura, 1985; Manahan, 1994). The detection of pesticide in soil, water and air (Hoffman et al., 2000; Goel et al., 2005; Harman-Fetcho et al., 2005; Loague et al, 2006; Lv et al., 2010; Riederer et al., 2010; Weber et al., 2010; Hayward et al., 2010), and reported adverse effects of pesticides to non-target organisms at environmentally relevant levels (Chandler et al., 1991; Clark et al., 1993; Margni et al., 2002; Schulz, 2004) has invoked public concern.

The off-site transport of pesticides and soil with runoff from agriculture is believed to be a large contributor to water quality degradation. It is estimated that 1 to 6% of soil-applied pesticides may be lost to aquatic environments in runoff and drainage from agricultural fields (Wauchope, 1978; Bengston et al., 1990). A number of pesticides have been detected in surface waters of agricultural watersheds (Baker and Richards, 1990; Thurman et al., 1992; Goolsby & Battaglin, 1993; Johnson et al., 1994) and research has demonstrated significant negative effects of pesticides on aquatic organisms and ecosystems resulting from nonpoint source agricultural runoff (Scott et al., 1990; Chandler and Scott, 1991; Savitz et al., 1994).

Tomatoes are one of the most economically important vegetables grown in the United States with average annual yields of 1.6 billion kilograms and 8.9 billion kilograms for fresh market and processing tomatoes, respectively, at an estimated value of nearly $2 billion (Davis et al., 1998). A cultivation method widely accepted by vegetable growers is the use of polyethylene mulch where a thin sheet of plastic is placed over a raised bed with bare-soil furrows between the beds. In 1999, polyethylene mulch was used on over 12 million hectares of land throughout the world; representing 450 thousand hectares in Europe, 9.7 million hectares in Asia, 200 thousand hectares in the Americas and 80 thousand hectares in Africa and the Middle East (Takakura & Fang, 2001). Polyethylene mulch is a preferred practice because it can warm the soil and control weeds; however, nearly 50 to 75% of the field is covered with an impervious surface which enhances runoff due to reduced water infiltration. Research has shown greater runoff volumes and soil erosion associated with polyethylene mulch relative to bare soil (McCall et al., 1988; Wan & El-Swaify, 1999). In addition, compared with conventional production agriculture, polyethylene mulch systems have an additional surface for pesticide adsorption/desorption which may enhance or impede chemical runoff and degradation rates (Vuik et al., 1990; Topp & Smith, 1992; Nerin et al., 1996).

Hairy vetch (*Vicia villosa* Roth) mulch, a vegetative cover crop, has been shown to be a profitable management practice for fresh market tomato production resulting in greater tomato yields and lower production costs than polyethylene mulch or bare soil (Kelly et al., 1995). Cover crops including hairy vetch have been shown to suppress weeds (Teasdale, 1996), act as a slow-release fertilizer (Ranells and Wagger, 1996), reduce soil erosion, increase soil organic matter, improve soil tilth (Smith et al., 1987), and increase soil infiltration and soil moisture (McVay et al., 1989). Field and laboratory studies have demonstrated that crop residues and vegetative mulches can reduce runoff, soil erosion, and the off-site transport of pesticides and nutrients from agricultural fields (Ghadiri et al., 1984; Dao, 1991; Sur et al., 1992; Zuzel and Pikul, 1993).

Approximately 32% of pesticide use in the United States results from non-agricultural pest control; including applications to protect structures, maintain lawns and landscapes, control weeds at roadsides and right-of-ways, maintain recreational areas and gardens, and repel and control nuisance and disease carrying pests. In 2000 and 2001, 19% of pesticide usage in the United States occurred in the home and garden sectors while 13% was accounted for by industrial, commercial and governmental sectors (Kiely et al., 2004).

More than 16 million hectares of land in the United States is estimated to be covered by tended lawn (Milesi et al., 2005). Managed turf is found in both private and public settings; as residential, commercial and public lawns, on golf courses and athletic fields, as sod farms, and in parks and cemeteries. In the late 1990s the urban/suburban pesticide market was estimated to be a billion dollars annually with pest control of turfgrass (e.g. professional lawn care, landscapers, nurseries, golf courses, sod farms and institutions) representing a significant portion of that market; approximately $500-$700 million (Joyce, 1998; Racke, 2000; Clark and Kenna, 2001). Golf courses contain some of the most intensely managed turf, which often requires multiple applications of pesticides at rates that may exceed those typically found in agricultural or home environments (Barbash and Resek, 1996; Gianessi and Anderson, 1996). Pesticides associated with the turfgrass industry have been detected in surface waters of urban watersheds (Cohen et al., 1999; Gilliom et al., 2006). Examples include spring and summer detections of carbaryl and diazinon at levels that exceeded criteria for protection of aquatic life (Hoffman et al., 2000), reports of dimethylamine salt of 2,4-dichlorophenoxyacetic acid (2,4-D), dicamba, and mecoprop in 85% of evaluated storm runoff events (Wotzka et al., 1994), and evidence of chlorpyrifos, diazinon and 2,4-D in surface waters throughout the year (Frick et al., 1998).

Fairways comprise approximately one-third of the managed turf of a typcial golf course (Watson et al., 1992; Lyman et al., 2007), which may be adjacent to surface waters such as streams, ponds and lakes. Golf course fairways and greens are often managed with core cultivation during the spring or fall to control thatch, stimulate root and shoot growth, alleviate surface compaction, and enhance water infiltration (Beard, 1973; White & Dickens, 1984; Turgeon, 1985; Carrow et al., 1987; Dunn et al., 1995, Callahan et al., 1998). Solid tine core cultivation requires a reduced amount of labor and is less disruptive to the surface of the turf but is believed to cause localized compaction. Cultivation with hollow tines typically involves removing cores from the turf, which are air-dried and brushed back into the open holes (Murphy et al., 1992). Despite the widespread use of core cultivation, little is known about the quantity of pesticides transported in runoff from turf managed with either solid tine or hollow tine core cultivation practices.

Evaluation of established and emerging management practices is important in order to understand their efficacy and sustainability. As benefits and improvements in management strategies are discovered they can be implemented; while practices with unexpected adverse consequences can be modified or replaced. Here we present research measuring the quantity of pesticides transported with runoff from agricultural (fresh market tomato production) and non-agricultural (golf course fairway turf) systems; to evaluate the influence of management practices to reduce the off-site transport of pesticides with runoff. Following quantification of pesticide mass transport, real-world runoff-to-surface water scenarios were used to extrapolate edge-of-plot runoff data to estimated environmental concentrations of pesticides in surface waters receiving the runoff. A comparison of surface water pesticide concentrations with published toxicity data assessed the ability of management practices to reduce ecological risk of pesticides from the evaluated agricultural and non-agricultural systems.

2. Materials and methods

2.1 Site description

Agricultural system: Runoff water was collected from tomato (*Lycopersicon esculentum* Mill) plots located at the Henry A. Wallace Beltsville Agricultural Research Center, Beltsville, Maryland, USA. The 2500-m^2 field is comprised of Mattapex silt loam (fine-silty, mixed, mesic Aquic Hapludults with 1.3 to 1.6% organic carbon content) with a 5 to 7% slope. The site was divided into sixteen plots, each with four raised beds (15 cm high, 27 m long, 0.9 m wide, and 1.5 m center-to-center), prepared in a north-south direction. A randomized complete block design was used to assign eight plots to tomato production and the remaining plots were planted with sweet corn (*Zea mays*). Tomato and corn plots were rotated annually to reduce pest pressure. Earthen berms were constructed around each plot to prevent water movement between the plots and to capture runoff only from the three central rows within each four-bed tomato plot.

Turf system: Experiments were conducted on 976 m^2 site located at the University of Minnesota Turf Research, Outreach and Education Center, Saint Paul, MN, USA. The soil was characterizes as Waukegan silt loam (sandy-skeletal, mixed superactive, mesic Typic Hapludolls) containing 55% silt, 29% sand, 16% clay and 3% organic carbon with a natural slope running east to west that was graded to 4% with less than 1% slope from north to south. The study area was sodded with L-93 creeping bentgrass (*Agrostis palustris* Huds.)

and divided into plots (24.4 m x 6.1 m, length x width), prepared in an east to west direction, 14 months prior to initiation of the reported studies. Prior to simulated precipitation events, plots were hydrologically isolated with removable berms, constructed from horizontally-split 10.2-cm schedule 40 PVC pipe, inverted to rest on the cut edges. Observations during runoff events showed no water movement under the PVC berms.

2.2 Management practices (treatments)

Agricultural system: During the month of September raised vegetable beds were constructed in plots assigned to the vegetative mulch treatment and planted with hairy vetch (*V. villosa*) seed on the beds and in the furrows between the raised beds. In early May the hairy vetch was finely chopped using a flail-mower to provide a vegetative mulch residue over the soil surface. By mid May, beds for the polyethylene treatments were constructed and drip irrigation lines were installed 8 to 10 cm from the plant row prior to the installation of the polyethylene. Furrows between raised beds covered with polyethylene remained as bare soil. During the last week of May, 'Sunbeam' tomato plant seedlings were transplanted in the center of each bed with a no-tillage planter to minimize the disruption of the mulches (polyethylene or hairy vetch residues). Immediately after transplanting, drip lines were added to the surface of the hairy vetch mulch beds approximately 8 to 10 cm from the plants. Tomato plants grown in the polyethylene and hairy vetch mulch received equal quantities of water through the irrigation system to maintain the plants during dry conditions. The quantity of water applied with the trickle irrigation system was not enough to produce surface runoff. Additional information on cultivation of hairy vetch cover crops and installation of polyethylene or hairy vetch mulch is given elsewhere (Abdul-Baki et al., 1996; Abdul-Baki et al., 1997; Rice et al., 2001).

Turf system: Creeping bentgrass turf was managed as a fairway with 1.25 cm height of cut (3 times weekly, clippings removed), topdressed with sand (weekly, 1.6 mm depth) and irrigated to prevent drought stress. The quantity of water applied with the maintenance irrigation was not enough to produce surface runoff. Core cultivation with either solid tines (0.95 cm diameter x 11.43 cm length) or hollow tines (0.95 cm internal diameter x 11.43 cm length) was performed twice (June 21st, Sept 28th) (Rice et al., 2010b). Cores removed with the HT were allowed to dry, broken into smaller pieces, and worked back into the turf. A back-pack blower and leaf rake removed the turf and thatch from the plot surface. Sand topdressing was not performed immediately after core cultivation or within a week of simulated precipitation and generation of runoff.

2.3 Pesticides

Agricultural system: Pesticides monitored in the tomato production experiment and reported in the present publication were as follows: Bravo® 720 fungicide (ISK Biosciences, Mentor, OH) containing 40.4% chlorothalonil (tetrachloroisophthalonitrile); Thiodan® 50 WP insecticide (FMC, Philadelphia, PA) containing 50% endosulfan (hexachlorohexahydromethano-2,4,3-benzodioxathiepin 3-oxide) and Asana® XL insecticide (Du Pont, Wilmington, DE) containing 8.4% esfenvalerate ((s)-cyano(3-phenoxyphenol)methyl(s)-4-chloro-alpha-(1-methylethyl) benzeneacetate). Details on the applied herbicide (metribuzin) and inorganic fungicide (copper hydroxide), can be found in previous publications (Rice et al., 2001; Rice et al., 2002). Properties of the active ingredients for pesticides reported in this manuscript are provided in Table 1.

	Water Solubility (20°C)	K_{OC}[b]	K_{OW}[c] (pH 7, 20°C)	Half Life (d)		
Pesticide[a]	(mg/L)	(ml/g)	(Log P)	Soil	Water-Sediment	Water
Chlorothalonil	0.81	850	2.94	22	0.1	0.1
Chlorpyrifos	1.05	8151	4.70	50	36.5	5
Endosulfan	0.32	11,500	4.75	50	---[d]	---
Esfenvalerate	0.001	5300	6.24	44	71	30
Flutolanil	8.01	735	3.17	233	320	90.5

[a]http://sitem.herts.ac.uk/aeru/footprint/en/index.htm.
[b]Soil organic carbon partition coefficient.
[c]Octanol-water partition coefficient.
[d]--- = no data.

Table. 1. Pesticide Properties.

Turf system: Commercially available pesticide products were tank mixed and applied at label rates to all plots perpendicular to runoff flow. The insecticide Dursban® 50W (Dow AgroSciences LLC, Indianapolis, IN) containing 50% chlorpyrifos (*O*,*O*-diethyl *O*-(3,5,6-trichloro-2-pyridinyl) phosphorothioate) and fungicide ProStar® 70WP (Chipco® Professional Products, Aventis CropScience) containing 70% flutolanil (*N*-[3-(1-methylethoxy) phenyl]-2-(trifluoromethyl) benzamide) are reported in the present publication. Properties of their active ingredient are provided in Table 1. Details on the tank mixed herbicides (2,4-D, dicamba, mecoprop-p), application equipment and spray characteristics are reported elsewhere (Rice et al., 2010a,b).

2.4 Precipitation

Agricultural system: A tipping-bucket rain gauge was used to measure the time and intensity of each precipitation event. Runoff resulting from natural precipitation was collected during the growing season, May to September. On occasions when rainfall runoff had not been produced within a week of pesticide applications, an overhead sprinkler system was used to create precipitation. The sprinkler system was erected around the field and between the plots with sprinkler nozzles that were 1.8 m above ground and spaced every 12 m, in order to give an even application of water to all plots simultaneously. This system delivered from 7.5 to 14.3 mm/hr rain intensities to the plots, which is similar to the average natural rainfall intensity (~ 11 mm/hr) during the growing season. Artificial rain events represented only 9 of the 41 precipitation events evaluated.
Turf system: A rainfall simulator was constructed following the design of Coody and Lawrence (1994) (United States patent 5,279,151), which delivered precipitation with a droplet size spectrum, impact velocity, and spatial uniformity characteristic of natural rainfall. Risers were spaced 3.7 m apart with nozzles and spinners suspended 2.7 m above the turf. Simulated precipitation was initiated 26 ± 13 h after pesticide application when the wind speeds averaged 0.8 ± 0.7 mps (1.8 ± 1.6 mph). Rain gauges (Taylor Precision Products) were distributed throughout each plot to quantify simulated precipitation. Measured rainfall rates were 29 ±6 mm/h; similar to storm intensities recorded in Minnesota, USA, during July through October. The duration of the simulated precipitation was 2.0 ± 0.5 h, which was chosen to assure 90 min of runoff had been generated from each plot. Details on the materials and dimensions of the simulator are provided elsewhere (Rice et al. 2010a,b).

2.5 Runoff collection

Runoff water samples and flow data were collected from either fiber-glass H flumes (agricultural study) or stainless-steel trapezoidal flumes (turf study) outfitted with bubbletube and sample-collection ports using automated runoff samplers (ISCO model 6700) equipped with flow meters (Isco model 730, Lincoln) (Rice et al., 2001; Rice et al., 2010a). Water samples were deposited into glass bottles, removed from the samplers and stored at -20 °C until laboratory processing and analysis. Up to 24 300-ml samples were collected from each runoff event.

2.6 Runoff processing and pesticide analysis

Water samples resulting from overland flow in the agricultural study contained soil particulates while those from the turf study were relatively clear. As a result, runoff from the agricultural study was characterized for both dissolved- and particulate-phase pesticides while runoff from the turf study was characterized for dissolved-phase pesticides.

Agricultural system: Due to the small sample volume and the large numbers of water samples collected in this study, composite samples from each plot for each runoff event were analyzed for dissolved-phase and particulate-phase pesticide concentrations. A detailed description of the processing and analytical methods are given elsewhere (Rice et al., 2001). Briefly, filtered water (0.7 µm) was extracted using a Varian SPME III autosampler (Varian, Palo Alto, CA) equipped with either a 100 µm polydimethylsiloxane or 85 µm polyacrylate fiber (Supelco, Bellefonte, PA). Analyses were carried out using a Hewlett Packard 5890 Series II gas chromatograph (Hewlett Packard, Santa Clarita, CA) with an electron capture detector. Chromatographic conditions for chlorothalonil and endosulfan analyses were as follows: J&W DB-5 column, 30 m x 0.25 mm i.d., film thickness of 25 µm (J&W Scientific, Folsom, CA), temperature program, injector temperature 270 °C, 150 °C, initial temperature, 2 min hold, 3 °C/min to 200 °C, 5 min hold, 10 °C/min to 260 °C, 1 min hold, detector temperature 270 °C. The limits of detection were 3500 ng/L for chlorothalonil, 9.5 ng/L for α-endosulfan and 13 ng /L for β-endosulfan. Esfenvalerate was extracted from 5-ml of runoff water using liquid-liquid extraction with 3, 5-ml aliquots of ethyl acetate. Organic extracts were combined and residual water was removed using a 2-g column of anhydrous $MgSO_4$ and concentrated to 1 ml with high purity N_2 gas and spiked with PCB #204 (60 ng) as an internal standard. Calibration standards were prepared in de-ionized water and extracted using the same method as the samples. De-ionized water control samples and blank water (5 ml) spiked with 400 ng Asana were extracted along with runoff samples. The limits of detection and extraction efficiencies for esfenvalerate were 540 ng/L, 96.6±13.5%. Analyses were carried out using the same chromatographic conditions described for chlorothalonil and endosulfan, with the exception of the temperature program which was as follows: 150°C initial temperature, 2 min hold, 10°C/min to 200°C, 3.5°C/min to 270°C, 0.40°C min to 275°C, 3.5 min hold.

In order to determine the particle-phase pesticide concentration, 50 ml from each sample was combined into an integrated sample from each plot for a total of 8 integrated samples from each rain event. Integrated samples were filtered through a glass fiber filter (Whatman GF/F, 0.7 µm nominal pore size) using a stainless steel filter holder. A quarter of each filter was extracted with 3:1 dichloromethane (DCM): acetone (chromatographic grade) for 6 h using a Soxhlet apparatus. Extracts were cleaned up using an LC-Alumina-N 2 g (Supelco, Bellefonte, PA) cartridge topped with 1 g anhydrous $MgSO_4$ to remove color, particle material, and water. An additional 15-ml of 1:1 DCM:acetone was passed through the clean up column and combined with the extract. Extracts were reduced using N_2 gas and exchanged into isooctane. Extraction efficiency of the method was evaluated by spiking filter papers used to filter runoff water from untreated soil with the target analytes and dibutyl chlorendate as a sample specific extraction efficiency determination. Recoveries ranged from 85.3 ± 4.9% to 91.2 ± 10.1%. Blank filter papers were also extracted and analyzed with samples and no interfering peaks were found. Extracts were analyzed using the chromatographic conditions described for dissolved-phase esfenvalerate, with the exception of the temperature program which was as follows: 150°C initial temperature, 2 min hold, 10°C/min to 200°C, 1 min hold, 3.0°C/min to 260°C, 10 min hold, 7.0°C/min to 280°C, 10 min hold. The method detection limits for the target analytes were: chlorothalonil 1.0 µg/L, α-endosulfan 0.63 µg/L, β-endosulfan 2.2 µg/L and esfenvalerate 49 µg /L.

Turf system: Water samples were processed by filtering 3-ml through a 0.45 µm nylon syringe filter (Whatman) followed by methanol (0.5 ml) to rinse the filter. Irrigation source water, background runoff water, and background runoff spiked with known quantities of pesticides served as blank and positive control samples. Each runoff sample was analyzed for pesticides. No samples were combined. Methanol rinsates of Petri dishes, containing pesticide residues for determination of actual application rates, were diluted with laboratory-grade organic-free water to 14% methanol to mimic the methanol and water content of the filtered runoff samples. Concentrations of each pesticide were measured by direct injection (500 µl) onto a high performance liquid chromatograph (Waters model 717plus autosampler and model 1525 binary pump) with a photodiode array detector (Waters model 2996: Waters) set at 230nm. Analytes were eluted from an Agilent C-18 column (150 mm long, 4.6 mm diameter, 5 µm packing) using two solvents [solvent A: laboratory-grade organic-free water (0.17% trifluoroacetic acid); solvent B: 82:18 methanol:acetonitrile] at a rate of 1 ml/min. Initial conditions, 60% B, were held for 2 min followed by a gradient ramped from 60 to 95% B in 23 min, a 3 min hold, then back to 60% B in 10 min with a 5 min hold. Recoveries were: 74 ± 23% for chlorpyrifos and 91 ± 8% for flutolanil. Method detection limits ranged from 2.5 to 3.7 µg/L. Limits of quantification for the target analytes were: chlorpyrifos 5.3 ± 0.9 µg/L and flutolanil 4.5 ± 0.8 µg/L.

2.7 Pesticide loads with runoff

Agricultural system: Seasonal pesticide loads represent the sum of dissolved- and particulate-phases for all runoff events collected from May to September. Loads from individual runoff events were based on a composite sample made up of combined individual flow-weighted samples that were collected throughout the runoff event for each plot. Dissolved-phase pesticide loads (mg/m^2) were calculated from measured runoff volumes from each plot (L/m^2) and the concentration of pesticides in the filtered runoff water (mg/L). Particulate-phase pesticide loads (mg/m^2) were quantified using measured runoff volumes for each plot (L/m^2), mass of total suspended solids per unit volume of runoff (g/L) and the concentration of the pesticide extracted from the particulates (mg/g).

Turf system: Pesticide loads (mg/m2) for individual runoff events were calculated from the sum of time-weighted samples collected throughout the runoff event. In summary, the mass of a pesticide transported with runoff for each time point was calculated from the measured pesticide concentration (mg/L) in the filtered runoff water, the flow rate at the time of sampling (L/min) and the time between samples (min) for the area of the turf plot (m^2). Graphical representation of runoff volumes and pesticide loads for individual samples throughout a runoff event are presented as hydrographs and chemographs elsewhere (Rice et al., 2010a,b).

2.8 Pesticide concentrations in surface water receiving runoff

Measured pesticide loads in edge-of-plot runoff were extrapolated to surface water concentrations using real-world runoff-to-surface water scenarios reported by others. Estimated environmental concentrations in the receiving surface water do not account for sorption or degradation of the pesticides and therefore were used as a relative comparison to evaluate the effectiveness of management practices to mitigate pesticide transport with runoff rather than represent a definitive available concentration.

Agricultural system: Dietrich & Gallagher (2002) measured dissolved copper concentrations in runoff from tomato fields managed with polyethylene mulch at the edge-of-field and in an adjacent creek receiving the runoff. Concentrations ranged from 20-236 μg/L in the edge-of-field runoff and were as high as 20 μg/L in a nearby creek. Using the lowest, highest and average chemical concentrations for the edge-of-field runoff and receiving surface water from their study, we determined nine dilution ratios (pesticide concentration in the runoff water to pesticide concentration in the creek) ranging from a 1:1 dilution to a 1:236 dilution, with a median dilution ratio of 1:15. Thus, in the present study, a 1:15 dilution was used to calculate environmentally realistic pesticide concentrations in surface water receiving edge-of-plot runoff from the polyethylene mulch plots.

A literature search afforded no similar dilution factor for hairy vetch mulch. Although edge-of-plot concentrations for hairy vetch mulch were also measured in our field experiments, using the 1:15 dilution to calculate surface water concentrations would not be appropriate; as the total pesticide loads in runoff from hairy vetch mulch were significantly less than the total pesticide loads in the runoff from polyethylene mulch. This decrease in load was primarily the result of smaller runoff volumes and less total soil lost as opposed to smaller pesticide concentrations in the runoff (Rice et al., 2001; Rice et al., 2002). Unlike concentration, load accounts for overall mass differences resulting from changes in both runoff volumes and quantity of soil lost with runoff. Therefore, pesticide concentrations in surface water associated with runoff from hairy vetch mulch were based on calculations using the percent reduction in pesticide load for edge-of-plot runoff from hairy vetch mulch relative to that from polyethylene mulch. For example, average seasonal loads of chlorothalonil in edge-of-plot runoff during the third season for polyethylene plots (70.1 mg/m^2/season) and hairy vetch plots (4.4 mg/m^2/season) represents a 94% reduction in mass of chlorothalonil entering the receiving surface water from hairy vetch plots. Therefore the creek concentration associated with hairy vetch mulch was calculated by reducing the polyethylene mulch creek concentration (192.4 μg/L, a 1:15 dilution of the edge-of-plot concentration 2885.4 μg/L) by 94%, resulting in a hairy vetch creek concentration of 12.1 μg/L, which represents the difference in mass of chlorothalonil entering the surface water.

Turf system: Pesticide loads in runoff from the turf were extrapolated to pesticide concentrations in surface water receiving the runoff based on sub-watershed characteristics and receiving surface water dimensions reported from a golf course located less than 20 miles from the study site (http://www.pca.state.mn.us/publications/stormwaterresearch-eaglelake.pdf, pond 4 sub-watershed). Using this real-world scenario, pesticide loads from the fairway turf plots (mg/m^2) were multiplied by the area (5641 m^2) of the golf course contributing runoff to the receiving surface water, and the estimated percentage of the golf course represented by fairway turf (0.33 or 33%) (Watson et al., 1992; Lyman et al., 2007), providing the overall mass of pesticide transported with runoff to the receiving surface water (440,000 L). Estimated pesticide concentrations of the surface water receiving runoff from fairway turf managed with solid tine or hollow tine core cultivation were compared to toxicological endpoints to evaluate which core cultivation practice would be the most efficient at mitigating ecological risk.

2.9 Statistical analysis

For both the agricultural and turf studies management practices were assigned to the plots using a randomized complete block design. Experiments were repeated for three consecutive field seasons with four replications of each treatment (type of mulch) for the agricultural study and for two simulated precipitation events with three replications of each treatment (type of core cultivation) for the turf study. Analyses of variance were performed to evaluate runoff volumes, soil loss and chemical loads, with the management practice as the single criteria of classification for the data (Steel & Torrie, 1997).

3. Results and discussion

3.1 Agricultural crop: fresh market tomato production

Precipitation and runoff volume. Runoff volumes were measured from each plot throughout three growing seasons (May to August). With the exception of a few runoff events, the volume of runoff collected from polyethylene mulch plots was 2 to 100 times more than runoff from hairy vetch plots for the 41 recorded runoff events. Precipitation and volumes of individual runoff events are provided in detail elsewhere (Rice et al., 2001). The seasonal water losses for the three growing seasons were 90.6, 55.4 and 146.0 mm per growing season for polyethylene plots and 36.8, 13.7 and 75.7 mm per growing season for hairy vetch plots; resulting in a 59, 75, and 48% reduction in runoff from tomatoes grown with the vegetative mulch (Figure 1A).

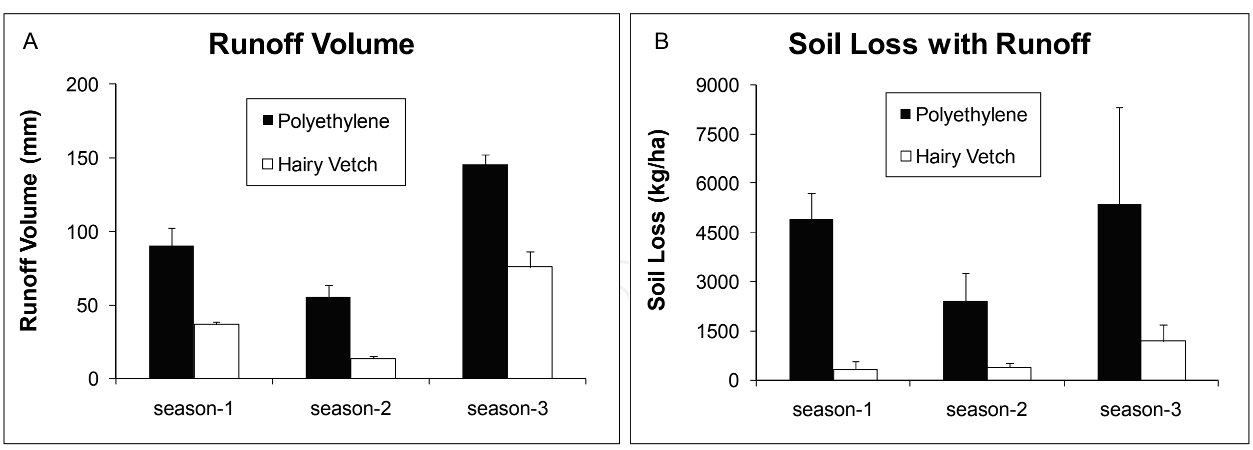

Fig. 1. Volume of runoff (A) and quantity of soil (B) transported in runoff from fresh market tomato production with polyethylene (plastic) and hairy vetch (vegetative) mulch.

Precipitation rate and infiltration rate determines the overall quantity of surface runoff. Vegetable production with polyethylene mulch may result in up to 75% of the soil surface covered with an impermeable film, depending on the width of the plastic covered tomato-beds and bare-soil furrows. McCall et al. (1988) and Wan & El-Swaify (1999) reported greater runoff volumes associated with the use of impermeable plastic mulch relative to bare soil. We have also observed that the addition of vegetative-mulch between polyethylene-covered tomato-beds reduces runoff volume compared to vegetable production with polyethylene-covered beds and bare-soil furrows (Rice et al. 2004, 2007). Plant residue of the vegetative mulch dissipates raindrop energy and increases surface roughness, both of which reduce the velocity of surface runoff allowing for greater infiltration within the furrows (Mannering & Meyer, 1963; Foster & Meyer, 1972). Elimination of the polyethylene mulch and use of vegetative-residue mulch on both the tomato-beds and in the surrounding furrows reduces runoff volumes do to greater infiltration as well as an increase in infiltration area since the impervious surface has been removed.

Soil erosion. The quantity of soil transported in the runoff ranged from 2.7 to 2000 kg/ha per event for polyethylene compared to 0.07 to 338 kg/ha per event for hairy vetch. Ten percent of the runoff events delivered >250 times more soil from the polyethylene plots (Rice et al., 2001). Average soil loss for the three growing seasons was 4921, 2418 and 5353 kg/ha per season for polyethylene plots and 328, 387 and 1179 kg/ha per season for hairy vetch mulch plots; representing a 93, 84 and 78% reduction in soil loss with runoff from the vegetative mulch (Figure 1B).

The significant reduction in soil erosion with runoff from tomatoes grown with hairy vetch mulch is likely the result of the hairy vetch plant residues dissipating raindrop energy and the anchoring characteristics of the roots providing increased structural stability in the vegetated soil (Mannering & Meyer, 1963; Foster & Meyer, 1972; Sur et al, 1992; Zuzel & Pikul, 1993). These factors contribute to greater infiltration of precipitation, reduced runoff volume and runoff velocity, and the significant reduction of suspended particulates transported with runoff. Measured flow rates of runoff from plots with polyethylene mulch were 1.2 to 7.5 times greater than from plots with hairy vetch mulch. Suspended sediment concentrations were 4 times greater in polyethylene runoff (polyethylene: 3,334 ± 0.87 mg/L; hairy vetch: 692 ± 1.5 mg/L).

Pesticides in runoff. Concentrations of pesticides associated with both the dissolved and particulate phases of the runoff were measured for each runoff event and combined with runoff and soil loss data to calculate total pesticide loads transported off-plot with runoff during each growing season. Chlorothalonil and endosulfan were measured in both the dissolved and particulate phases while esfenvalerate was absent from the dissolved phase (Figure 2). Greater loads of all three pesticides were associated with runoff from polyethylene mulch than hairy vetch mulch regardless of the phase (dissolved or particulate) evaluated. When total pesticide loads were considered, hairy vetch mulch reduced pesticide loads with runoff by 70 to 97% compared to polyethylene mulch. Details on the dissolved and particulate phase pesticide concentrations and loads for individual runoff events can be obtained elsewhere (Rice et al., 2001).

Although the fungicide (chlorothalonil) and insecticides (endosulfan, esfenvalerate) were applied to the tomato plants, inevitably, a percent of the applied pesticides are either washed off the foliage onto the mulch or are directly applied to the mulch during foliar application. Rainfall may interact with chemical residues in the top centimeter of soil, termed the extraction- or mixing-zone (ISU, 1992; Baker and Mickelson, 1994; Wauchope, 1996). The compromised infiltration capacity of the polyethylene-covered vegetable-beds and reduced leaching of pesticides below the extraction zone explains, in part, the increased availability of pesticides for transport with runoff from the plastic mulch system. The

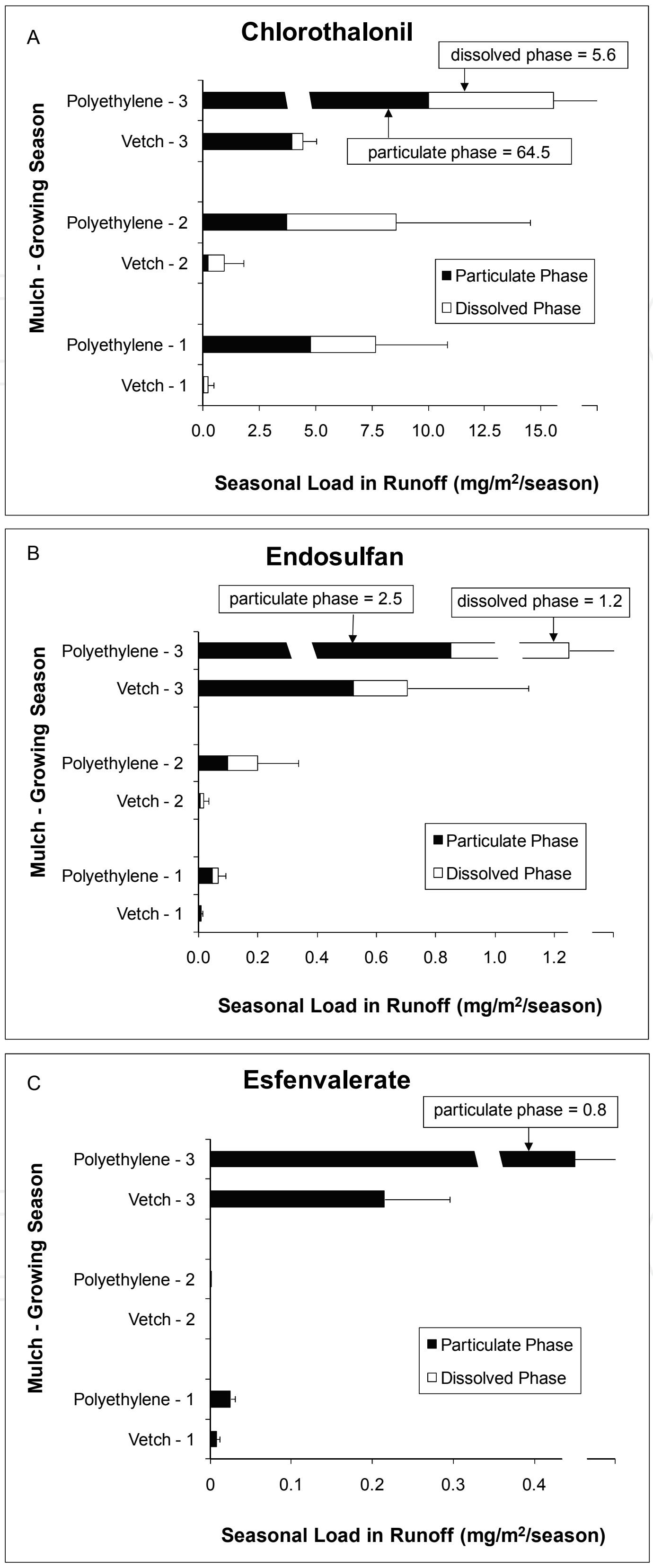

Fig. 2. Quantity of chlorothalonil (A), endosulfan (B) and esfenvalerate (C) transported in runoff from fresh market tomato production using polyethylene (plastic) or hairy vetch (vegetative) mulch.

adsorption and desorption of pesticides to the mulch will also influence the pesticides' availability to be transported with surface runoff. The adsorption of pesticides to polyethylene mulch, which has been shown to be influenced by the chemical properties of the pesticide as well as the density of the polyethylene (Vuik et al., 1990; Topp & Smith, 1992), may be playing an important role in the pesticide loading profile of the runoff. When a chemical is weakly adsorbed to the polyethylene mulch the loading profile would show a large pulse at the beginning of the runoff event followed by a sharp decline. Pesticides that are more strongly adsorbed to the polyethylene material would be illustrated by a slow bleed of chemicals off the plastic that may occur over the entire runoff event. McCall et al. (1988) reported the peak concentration of endosulfan in runoff from polyethylene mulch occurred at the beginning of the rainfall event compared to the peak concentration in the bare soil runoff that occurred in tandem with the peak flow. This illustrates endosulfan was more weakly adsorbed to polyethylene than soil. We found a great difference in the loading profile chemographs of endosulfan and chlorothalonil in the dissolved phase of runoff from polyethylene mulch compared to hairy vetch mulch (Rice et al., 2001). Statistical analysis revealed chlorothalonil loads in the dissolved phase of runoff were more associated with runoff volume than pesticide concentration in the runoff for both polyethylene and hairy vetch mulch (chlorothalonil: volume r^2 = 0.57 to 0.83, concentration r^2 = 0.00 to 0.06). Runoff volume and pesticide concentration in the runoff water were equally important for endosulfan (endosulfan: volume r^2 = 0.48 to 0.92, concentration r^2 = 0.71 to 0.99). Esfenvalerate was only measured in the suspended particulates, which corresponds to its very low water solubility (Table 1). Management practices that enhance or reduce either runoff volume or soil loss with runoff will influence the mass of pesticides transported with runoff. Additional studies on the sorption interactions of pesticides with polyethylene and plant residues of the hairy vetch will be needed to fully understand pesticide transport with runoff from these two mulch systems.

3.2 Turf: golf course fairway

Precipitation and runoff volume. Simulated precipitation and evaluation of resulting runoff occurred during the months of August and September while the turf was actively growing (mean air temperatures approximately 21 ˚C (70 ˚F)). Core cultivation with solid or hollow tines occurred 63 d prior to initiation of the first simulated rainfall event, while the period of time between the second core cultivation and simulated precipitation was only 2 d. The greater time lag between core cultivation and the runoff study for the first event was a result of delays in the construction of the rainfall simulator. Although differences were noted in the results of the 63 d (event – 1) and 2 d (event – 2) data the overall trends observed between solid tine and hollow tine core cultivation remained the same (Rice et al., 2010b). It is important to note the time between pesticide application and runoff was similar for both runoff events (26 ± 13 h).

Overall, runoff volume was reduced in fairway turf plots managed with hollow tine core cultivation compared to solid tine core cultivation. The total volume of runoff measured from turf managed with hollow tines was 10% (63 d) and 55% (2 d) less than the total volume quantified from turf managed with solid tines (63 d: hollow tine = 21.1 ± 6.2 mm, solid tine = 23.4 ± 7.4 mm; 2 d: hollow tine = 12.5 ± 0.9 mm, solid tine = 28.0 ± 16.1 mm) (Figure 3A). Hydrographs revealed reduce runoff volumes associated with hollow tine core cultivation in 81% (63 d) and 87% (2 d) of the samples (Figure 3B).

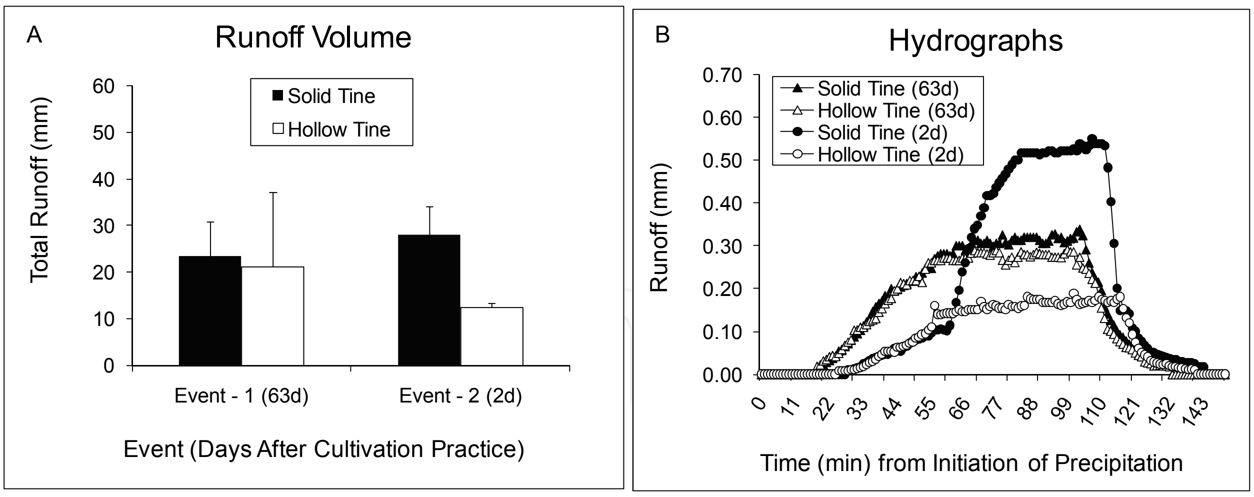

Fig. 3. Total volume of runoff (A) and runoff hydrographs (B) from golf course fairway turf managed with solid tine core cultivation or hollow tine core cultivation 63 d and 2 d prior to precipitation.

Solid tine core cultivation has been shown to result in localized compaction with the most sever compaction at the base of the zone of cultivation (Murphy et al., 1992). Hollow tine core cultivation has also been shown to result in compaction along the sidewalls and base of the coring; however, sidewall compaction dissipated while bottom compaction remained after 95 d (Petrovic, 1979). Our field observations and measurements showed greater infiltration with hollow tine core cultivation compared to solid tine core cultivation with the greatest difference between cultivation practices occurring shortly after treatment (2d) and decreasing with time (63 d) (Rice et al., 2010b). We speculate the greatest difference in soil physical properties was most prominent shortly after hollow tine or solid tine core cultivation; which diminished as roots grew, compaction dissipated, and core channels were covered or filled. Other researchers have reported greater air porosity and saturated water conductivity in turf managed with hollow tines compared to solid tines, and enhanced water infiltration in turf managed with hollow tine core cultivation compare to untreated turf (Murphy et al., 1992; Baldwin et al., 2006; McCarty et al., 2007).

The quantity of applied precipitation measured as surface runoff represented 28 to 62% of the applied rainfall depending on the type of core cultivation and time duration between core cultivation and precipitation (2d: hollow tine = 28 ± 2%, solid tine = 62 ± 25%; 63 d: hollow tine = 36 ± 11%, solid tine = 41 ± 13% (Rice et al., 2010b). Shuman (2002) observed 37 to 44 % of applied water resulted as runoff from fairways of Tifway bermudagrass (*Cynodon dactylon* (L.) Pers.), which received 50 mm of simulated precipitation, 2 d following irrigation to field capacity. Kauffman and Watschke (2007) observed three to 21% of applied simulated precipitation was measured as runoff from bentgrass and perennial ryegrass turf managed with hollow tine core cultivation. They attributed variations in runoff volumes to differences in antecedent soil moisture, slope and environmental conditions. For our experiments, soil moisture measurements for both cultivation practices were 46 ± 7% (n = 54) water holding capacity 3 h prior to initiation of the simulated precipitation and 67 ± 6% (n = 54) water holding capacity 2 h following simulated precipitation. The slope of each plot was 4% and simulated precipitation and collection of runoff were performed in side-by-side paired comparisons (hollow tine versus solid tine for each replication) with runoff data normalized to the measured quantity of precipitation applied to each plot (n = 11 per plot).

Therefore the reduction in percentage of applied precipitation resulting as surface runoff from the hollow tine plots versus solid tine plots is the effect of the core cultivation practices.

Pesticides in runoff. Plots receiving hollow tine core cultivation to manage thatch 63 d prior to runoff showed a 15% reduction in flutolanil loads (solid tine = 29.4 ± 11.2 mg/m^2, hollow tine = 24.9 ± 10.6 mg/m^2) while chlorpyrifos loads were similar (solid tine = 0.24 ± 0.01 mg/m^2, hollow tine = 0.28 ± 0.17 mg/m^2) (Figure 4). Following the second core cultivation, 2 d prior to initiation of simulated precipitation and runoff, hollow tine plots displayed a reduction in both flutolanil and chlorpyrifos loads relative to the solid tine plots with a 55% decline in total loads of flultolanil (solid tine = 29.0 ± 17.2 mg/m^2, hollow tine = 13.2 ± 0.2 mg/m^2) and a 57% reduction in total loads of chlorpyrifos (solid tine = 0.71 ± 0.34 mg/m^2, hollow tine = 0.31 ± 0.02 mg/m^2). Solid tine core cultivation pushes the soil aside to create channels while hollow tine core cultivation removes cores and returns the soil back to the turf. As a result one would anticipate increased soil compaction with the solid tine cultivation and greater accessibility of soil adsorptive sites with the hollow tine cultivation. This would influence infiltration and hydraulic conductivity (Murphy et al., 1992; Baldwin et al., 2006; McCarty et al., 2007) as well as pesticide availability for transport (Liu et al., 1995; Gardner et al., 2000; Raturi et al., 2005). Analysis of pesticide loads with runoff volumes and pesticide concentrations in the runoff showed loads were attributed to runoff volume more than chemical concentrations for both management practices (volume r^2 = 0.78 to 0.90, concentration r^2 = 0.05 to 0.22). The greater association of pesticide load with runoff volume explains in part the increased pesticide transport associated with the solid tine plots compared to hollow tine plots and the greater difference in pesticide loads between cultivation practices at 2 d compared to 63 d.

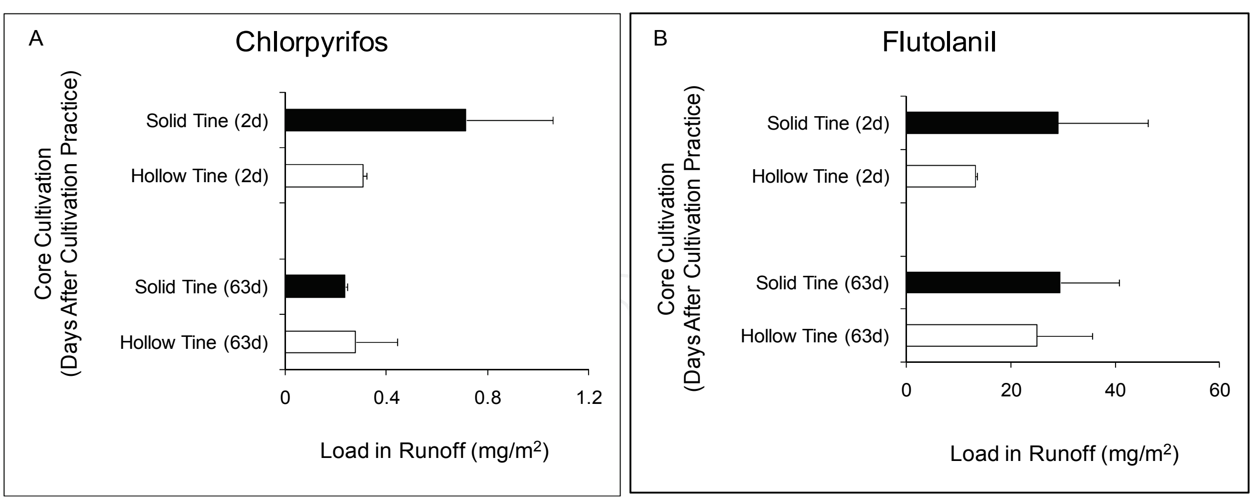

Fig. 4. Quantity of chlorpyrifos (A) and flutolanil (B) transported in runoff from golf course fairway turf managed with solid tine core cultivation or hollow tine core cultivation 63 d and 2 d prior to precipitation.

In addition to numerous environmental and management factors that contribute to the availability of pesticides for movement with overland flow, the physical and chemical properties of the pesticide will also influence the quantity of applied active ingredient observed in the runoff. A greater percentage of the applied flutolanil (less than 10%) was measured in the runoff compared to chlorpyrifos (less than 2%), which corresponds to the greater water solubility and smaller soil organic partition coefficient of flutolanil (Table 1). The quantity of chlorpyrifos and flutolanil quantified in the runoff are in range of the values reported by others who have observed less than 2 to 15% of applied pesticides measured in runoff from turf (Wauchope et al., 1990; Cole et al., 1997; Ma et al., 1999; Armbrust & Peeler, 2002). Chemical degradation was not influential in the present study as the time from chemical application to runoff (30 ± 8 h) was much less than the reported half lives of the compounds of interest (5 to 320 d) (Table 1). Chemographs of chlorpyrifos and flutolanil and additional information on the transport of applied nutrients and herbicides from managed turf are published elsewhere (Rice et al., 2009; Rice et al., 2010a,b). In general, chemographs of flutolanil and chlorpyrifos quickly diverged from the hydrograph compared to more water soluble herbicides, which had chemographs that closely resembled the runoff hydrograph during the first 50 minutes of runoff (Rice et al., 2010a).

3.3 Mitigation of ecological risk with management practices

The effectiveness of management practices to reduce ecological risk of pesticides transported in runoff from agricultural crops or managed turf was evaluated. Edge-of-plot runoff data was extrapolated to surface water concentrations using reported real-world scenarios of runoff from tomato production with polyethylene mulch into an adjacent creek (Dietrich & Gallagher, 2002.) and runoff from a golf course fairway into an adjacent pond (http://www.pca.state.mn.us/publications/stormwaterresearch-eaglelake.pdf, pond 4 sub-watershed). These estimated environmental concentrations of pesticides in the receiving surface waters were compared to published toxicity data. The toxicity of compounds to organisms can be evaluated using endpoints such as behavioral, reproductive and developmental effects as well as lethality. Although changes in behavior or effects on reproduction and development are more sensitive endpoints, a common and more readily quantifiable endpoint used in risk assessments is the median lethal concentrations (LC50) or the concentration of compound that results in mortality of fifty percent of the exposed organisms during a measured exposure period. A summary of median lethal concentrations used in the assessment of the agricultural and turf management practices are presented in Table 2.

Agricultural crop: tomato production. Concentrations of the fungicide chlorothalonil and the insecticides endosulfan and esfenvalerate in a surface water receiving runoff from tomatoes grown in polyethylene mulch or hairy vetch mulch are presented in Figure 5. Although the surface water concentrations represent a 1:15 dilution of the runoff, quantities of these pesticides in surface waters receiving runoff from polyethylene mulch exceeded the median lethal concentration for five fish (common carp, bluegill, striped bass, rainbow trout and fathead minnow), three crustaceans (freshwater prawn, giant river prawn and shrimp) and a mollusk (fingernail clam), during two or more of the growing seasons evaluated (Figure 5, Table 2). With a few exceptions, replacing polyethylene mulch with hairy vetch mulch reduced surface water concentrations of the pesticides to levels below the median lethal concentrations (Fig. 5). Exceptions were noted during the third season when pesticide loads were greatest and surface water concentrations of endosulfan exceeded the median leathal concentration for two fish (fathead minnow and striped bass) and two crusteaceans (shrimp and giant river prawn) and esfenvalerate exceeded the median lethal concentration for two fish (bluegill and rainbow trout) regardless of the type of mulch (polyethylene or hairy vetch). Concentrations of chlorothalonil, endosulfan and esfenvalerate in the surface water were below median lethal concentrations for three amphibians (green frog, bog frog and leopard frog) and two mollusks (bivalve and mussel).

Managed turf: golf course fairway. Estimated environmental concentrations of pesticides in a surface water receiving runoff from turf managed as a golf course fairway resulted in concentrations of chlorpyrifos from 1.0 to 3.0 μg/L and flutolanil from 55 to 123 μg/L. Specific concentrations associated with runoff from turf managed with solid tines compared to hollow tines are provided in Figure 6. With the exception of chlorpyrifos in the first runoff event occurring 63 days after core cultivation, replacing solid tine core cultivation with hollow tine core cultivation reduced concentrations of pesticides in the surface water receiving runoff. This included three herbicides that were co-applied with chlorpyrifos and flutolanil (data not shown) (Rice et al., 2010b). For the second runoff event, occurring 2 days after core cultivation, chlorpyrifos concentrations in the surface water associated with runoff from the plots managed with solid tines exceeded median lethal concentrations of three fish (common carp, bluegill and striped bass) and three crustaceans (copepod, shrimp and white river crayfish) (Table 2, Figure 6). Managing thatch with hollow tine core cultivation compared to solid tine core cultivation reduced surface water concentrations of chlorpyrifos to levels below the median lethal concentration of the copepod, white river crayfish, common carp and bluegill. However, the sensitivity of shrimp and striped bass to

Figure letter[a]	Scientific name	Common name	LC50 (μg/L) [exposure duration (d)][b]				
			Chlorothalonil	Chlorpyrifos	Endosulfan	Esfenvalerate	Flutolanil
	Amphibians						
A	*Rana clamitans*	Green Frog	----[c]	235.9 [2][d,e]	15 [13][f]	----	----
B	*Rana limnocharis*	Bog Frog	245 [2][g]	2401 [2][g]	12 [2][g]	28 [2][g]	----
C	*Rana pipiens*	Leopard Frog	----	----	----	7.29 [4][h]	----
	Crustaceans						
D	*Copepoda*	Copepod Subclass	----	2.13 [2][i]	----	----	----
E	*Macrobrachium dayanum*	Freshwater Prawn	----	----	6.2 [1][j]	----	----
F	*Macrobrachium rosenbergii*	Giant River Prawn	----	----	0.2 - 0.93 [4][k]	----	----
G	*Paratya australiensis*	Shrimp	16 [4][l]	0.1 [3][m]	0.51 - 0.96 [2][n]	----	----
H	*Procambarus acutus acutus*	White River Crayfish	----	2 [4][o]	----	----	----
I	*Streptocephalus sudanicus*	Fairy Shrimp	----	3.48 [2][p]	----	----	----
	Fish						
J	*Cyprinus carpio*	Common carp	110 [2][q]	1.8 [1][r]	9.5 [4][s]	----	≥ 2900 [2][t]
K	*Lepomis macrochirus*	Bluegill	26 - 62 [4][u]	1.7 - 2.5 [4][v]	3.3 [1][v]	0.31 [4][w]	5400 [4][u]
L	*Morone saxatilis*	Striped Bass	----	0.58 [4][x]	0.22 - 0.43 [4][y]	2.17 [1][z]	----
M	*Oncorhynchus mykiss*	Rainbow trout	40.2 [1][aa]	15 [1][v]	8.89 [2][bb]	0.07 [4][u]	5400 [4][u]
N	*Pimephales promelas*	Fathead Minnow	----	120 - 170 [4][cc]	1.84 [1][dd]	0.616 [2][ee]	4800 [4][u]
	Mollusks						
O	*Lamellidens corrianus*	Bivalve	----	----	17 - 44 [4][ff]	----	----
P	*Lamellidens marginalis*	Mussel	----	----	6 - 40 [4][ff]	----	----
Q	*Sphaerium sp.*	Fingernail clam	----	----	----	1.6 [2][gg]	----

[a]Letters referenced in Figures 5 & 6. [b]Data and references available at http://cfpub.epa.gov/ecotox/ecotox_home.cfm. [c]---- = no data. [d]Effect measured for EC50 = stimulus avoidance. [e]Wacksman et al., 2006. [f]Harris et al., 1998. [g]Pan & Liang, 1993. [h]Materna et al., 1995. [i]Siefert, 1987. [j]Omkar & Murti, 1985. [k]Lombardi et al., 2001. [l]Davies et al., 1994. [m]Olima et al., 1997. [n]Hose & Wilson, 2005. [o]Carter & Graves, 1972. [p]Lahr et al. 2001. [q]Hashimoto & Nishiuchi, 1981. [r]Dutt & Guha, 1988. [s]Shivakumar & David, 2004. [t]Nishiuchi et al., 1985. [u]Office of Pesticide Programs, 2000. [v]Mayer & Ellersieck, 1986. [w]Fairchild et al., 1992. [x]Korn & Earnest, 1974. [y]Fujimura et al., 1991. [z]Geist et al., 2007. [aa]Davies & White, 1985. [bb]Capkin et al., 2006. [cc]Jarvinen & Tanner, 1982. [dd]Kleiner et al., 1984. [ee]Bouldin et al., 2004. [ff]Mane and Muley, 1984. [gg]Lozane et al., 1989.

Table 2. Median lethal concentrations (LC50) of the selected pesticides.

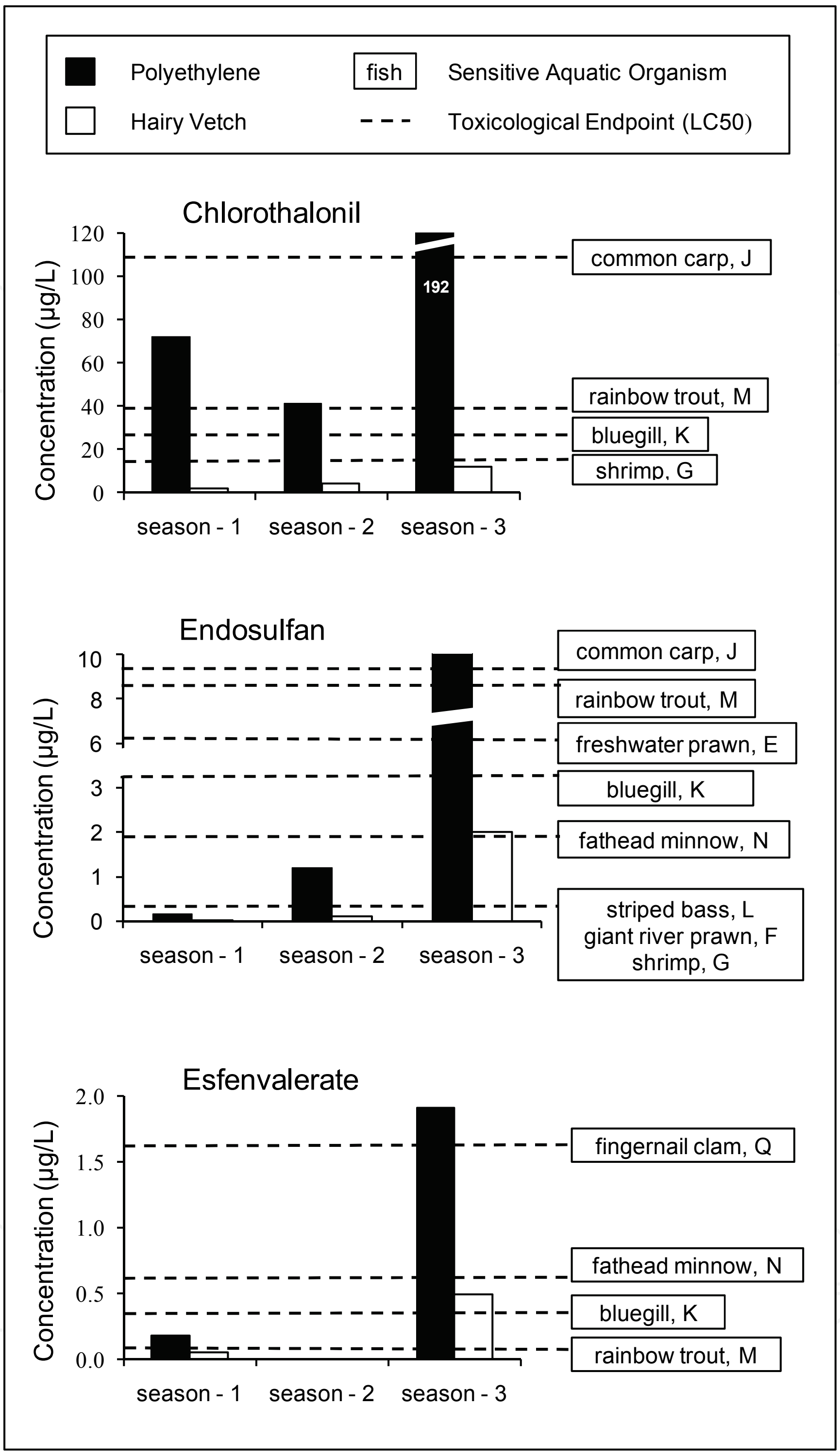

Fig. 5. Estimated environmental concentrations of chlorothalonil, endosulfan, and esfenvalerate in a surface water receiving runoff receiving runoff from fresh market tomato production with polyethylene (plastic) mulch or hairy vetch (vegetative) mulch. The broken lines represent the median lethal concentrations of sensitive aquatic organisms named in the attached boxes. Capital letters following the name of the aquatic organisms correspond to the letters given in the first column of Table 2, which provides the toxicological data in greater detail.

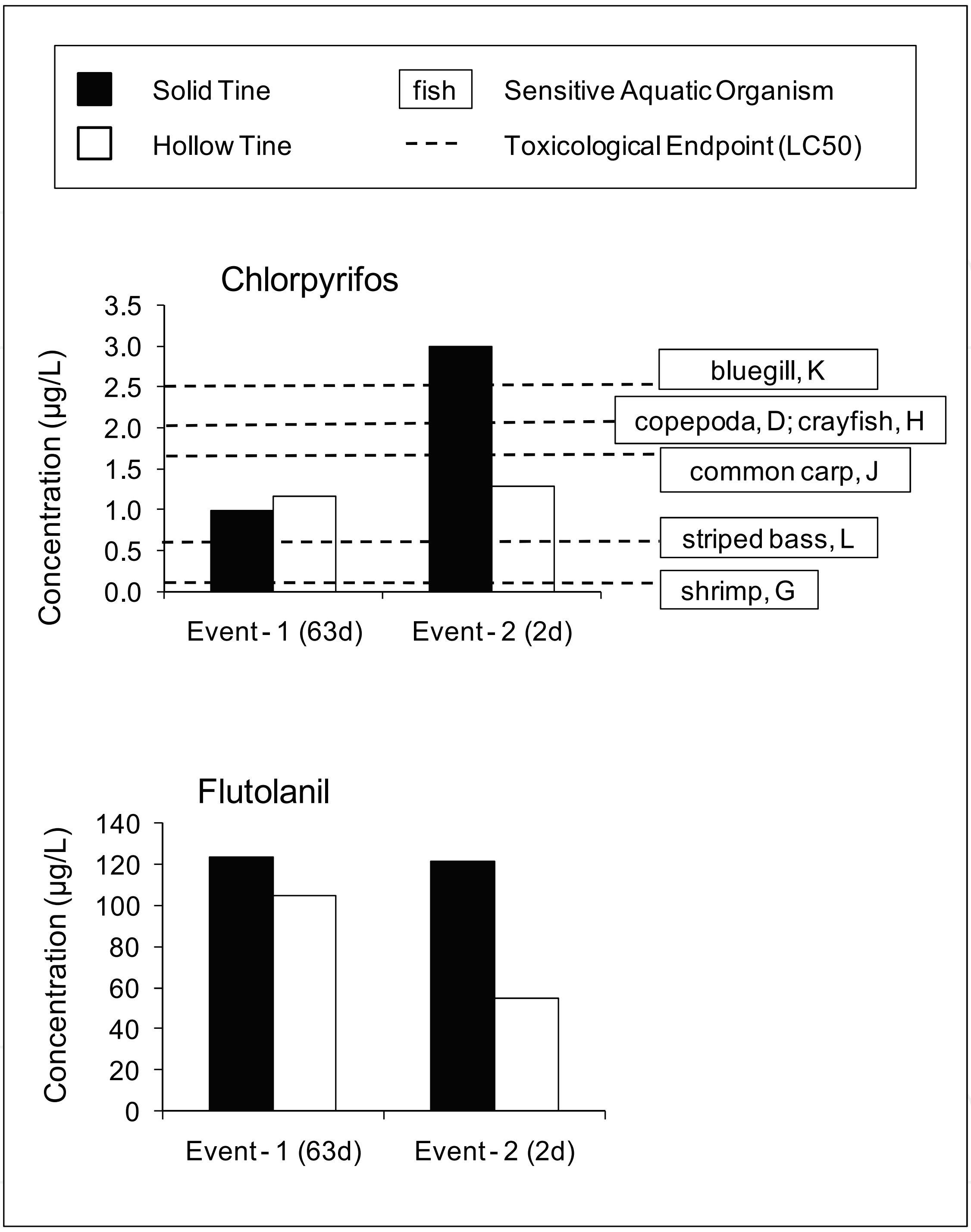

Fig. 6. Estimated environmental concentrations of chlorpyrifos and flutolanil in a surface water receiving runoff from creeping bentgrass turf managed as a golf course fairway with solid tine core cultivation or hollow tine core cultivation 63 days and 2 days prior to runoff. The broken lines represent the median lethal concentrations of sensitive aquatic organisms named in the attached boxes. Capital letters following the name of the aquatic organisms correspond to the letters given in the first column of Table 2, which provides the toxicological data in greater detail. Surface water concentrations of flutolanil were 24 to 98 times below the median lethal concentrations of the aquatic organisms evaluated, therefore no sensitive aquatic organisms are shown on the graph for flutolanil.

chlorpyrifos was great enough that estimated surface water concentrations exceeded the median lethal concentration regardless of the turf cultivation practice (solid tines or hollow tines). In contrast, surface water concentrations of flutolanil were 24 to 98 times below the median lethal concentrations of the four fish evaluated (common carp, bluegill, rainbow trout, and fathead minnow).

In summary, median lethal concentrations of chlorothalonil, chlorpyrifos, endosulfan, esfenvalerate and flutolanil for 17 organisms were compared with estimated environmental concentrations of surface waters that received runoff from either vegetable production with polyethylene mulch compared to hairy vetch mulch or golf course fairway turf managed with solid tine compared to hollow tine core cultivation. These organisms were chosen to represent amphibians, crustaceans, fish and mollusks that spend part or all of their life in freshwater creeks, streams, ponds or lakes. In 18 of the 39 exposure scenarios (Table 2) changing the management practice reduced the ecological risk of the pesticide in at least one of the seasons or events, bringing the surface water concentration below the reported median lethal concentration for the evaluated organism (Figures 5&6, Table 2, chlorothalonil: organisms G, J, K, M; chlorpyrifos: organisms D, H, J, K for event-2; endosulfan: organisms E, J, K, M for season-3 and F, G, L for season-2; esfenvalerate: organisms M for season-1 and N, Q for season-3). In some circumstances the sensitivity of the organism to the pesticide was great enough that estimated surface water concentrations exceeded the median lethal concentration regardless of the management practice (Figures 5&6, Table 2, chlorpyrifos: organisms G, L; endosulfan: organisms F, G, L, N for season-3; esfenvalerate: organisms K, M for season-3). Similarly, changes in management practice did not significantly influence the risk of pesticides to organisms with median lethal concentration above the estimated environmental concentration in the diluted surface water (Figures 5&6, Table 2, chlorothalonil: organism J for seasons-1&2, B (not shown on Figure 5); chlorpyrifos: organisms D, H, J, K for event-1 and A, B, I, M, N (not shown on Figure 6); endosulfan: organisms E, J, K, M for seasons-1&2, F, G, L for season-1 and A, B, O, P (not shown on Figure 5); esfenvalerate: organisms K, N, Q for season-1 and B, C, L (not shown on Figure 5); flutolanil: organisms J, K, M, N (not shown on Figure 6)). The toxicity of compounds to organisms can be evaluated using sublethal effects such as induction of enzyme systems, behavioral traits, or reproductive and developmental effects; which are often more sensitive than the end point of lethality (Klaassen, 1996). The impact of replacing impermeable polyethylene mulch with the vegetative hairy vetch mulch in vegetable production and replacing solid tine core cultivation with hollow tine core cultivation when managing turf will be further evident when more sensitive toxicological endpoints are evaluated.

4. Conclusions

The research described in this chapter measured the quantity of pesticides transported with runoff from agricultural systems (fresh market tomato production with polyethylene mulch or hairy vetch mulch) and turfgrass systems (golf course fairway turf managed with solid tine or hollow tine core cultivation) in order to evaluate the capacity of management practices to reduce the off-site transport of pesticides. Reported real-world runoff-to-surface water scenarios were used to extrapolate pesticide loads in runoff to estimated environmental concentrations of pesticides in surface waters receiving the runoff. Surface water concentrations of the pesticides were compared with published toxicity data to assess reductions in the ecological risk associated with implementation of the management practices. The reduced runoff volume and pesticide loads measured in runoff from the hairy vetch mulch and hollow tine core cultivation suggests these management practices are more sustainable for the agricultural and turf systems, respectively. This was further illustrated by reduced ecological risk in 18 of 39 pesticide exposure scenarios in which changing the management practice resulted in surface water concentration of pesticides below the reported median lethal concentrations for the evaluated aquatic organisms. The scenarios presented in this study do not represent absolute risk as they do not consider degradation and bioavailability of the pesticide, potential synergistic interactions between pesticides, effects of pesticides on other ecosystem components, or the life cycle of the species (Matthews et al., 2002). However, these assessments are informative for identifying management practices that reduce ecological risk by maintaining pesticides at targeted locations. According to the United States Environmental Protection Agency, integrated pest management relies on a combination of evaluations, practices, and options to manage pests with an effective and environmentally sensitive approach that is economical and presents the smallest potential hazard to people, property, and the environment (http://www.epa.gov/pesticides/factsheet/ipm.htm). Our results demonstrate that management practices can enhance the sustainability of intensely managed biotic systems; improving efficacy of pesticides at targeted locations while reducing adverse impacts to non-target organism. In addition, management practices can be instrumental in maintaining the use of pesticides as a tool in integrated pest management, by providing the least possible hazard of pesticides to the environment.

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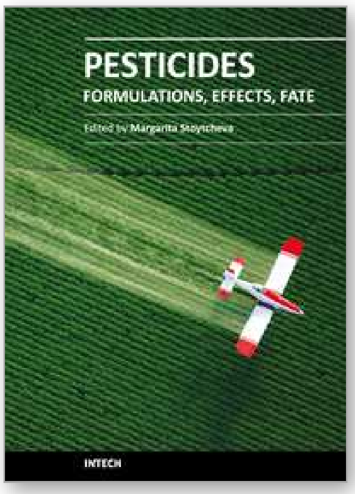

Pesticides - Formulations, Effects, Fate

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This book provides an overview on a large variety of pesticide-related topics, organized in three sections. The first part is dedicated to the "safer" pesticides derived from natural materials, the design and the optimization of pesticides formulations, and the techniques for pesticides application. The second part is intended to demonstrate the agricultural products, environmental and biota pesticides contamination and the impacts of the pesticides presence on the ecosystems. The third part presents current investigations of the naturally occurring pesticides degradation phenomena, the environmental effects of the break down products, and different approaches to pesticides residues treatment. Written by leading experts in their respective areas, the book is highly recommended to the professionals, interested in pesticides issues.

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